

Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185

Abstract

The technology base formed by the development of high peak power simulators, laser drivers, FEL's, and ICF drivers from the early 60's through the late 80's is being extended to high average power short-pulse machines with the capabilities of supporting new types of manufacturing processes and performing new roles in environmental cleanup applications. This paper discusses a process for identifying and developing possible commercial applications, specifically those requiring very high average power levels of hundreds of kilowatts to perhaps megawatts. We will discuss specific technology requirements and give examples of application development efforts. The application development work is directed at areas that can possibly benefit from the high specific energies attainable with short pulse machines.

Introduction

The electron and ion beams from large, single shot, pulsed power machines developed over the last 30 years for defense related applications offer unusual combinations of energy density, temperature, and pressure not attainable in more conventional thermal processes. Specific accelerator developments, such as the use of large-scale saturable magnetic switches^(1,2,3), high peak power linear induction voltage adders^(4,5), and large-area electron and ion diodes^(6,7,8), require the addition of thermal heat management techniques and an understanding of reliability issues to allow them to be used in high average power industrial processing applications. Selection of energy efficient technologies, with potential for long life reliable operation, require demonstrations before they can achieve acceptance in the commercial marketplace.

An Approach to Application Development

A program for developing a new high average power short-pulse electron or ion beam application should address the following tasks:

1) General concept definition - This phase of the development process combines input from all areas of physics and chemistry to identify radiation and particle interactions with materials that have potential matches to a set of defined problems. Inputs for new technology application areas would be determined through reviews of small scale laboratory demonstrations in related areas, examination of problems with high payoff and no competing low-technology solutions, and inputs on needs from manufacturing or waste management firms.

2) Scoping calculations - Preliminary calculations require the expertise of a team of specialists to assess the magnitude of the problem and the capability of the technology to match a possible application. Basic chemistry and physics issues would be conceptually reviewed and fundamental calculations and simulations would be performed to establish the possibility of a viable solution.

3) User interfacing - Early interfacing with possible users requires a project representative to clearly identify needs, promote possible technology advantages, and get inputs on limitations imposed by the users work environment. Early, and continual, user input would guide the overall project direction.

4) Concept feasibility analysis - The concept feasibility analysis provides the technical review to evaluate the worth of the technology for the identified needs. Rough costing estimates would be included at this stage to focus on value added by the process compared to possible capital and operating costs and costs of competing technologies.

5) Feasibility experiments and demonstrations - Demonstration experiments would be done in a manner that addresses the key chemistry and physics issues of the specific application.

6) Integrating applications with industrial equipment suppliers - High volume production of accelerators and material handling equipment would be addressed through a cooperative program with a team of industrial partners.

High Average Power, Short-Pulse Beam Applications

Many applications of electron beam, ion beam, or x-ray processing have been described in the literature^(9,10,11,12). This paper will focus on applications, not already in the commercialization stage, that require short (~50 ns to 500 ns) electron or ion pulses with energies between 500 keV and 10 MeV at power levels greater than 200 kW. These beam power levels can be provided by a new class of accelerators using semiconductor switches, magnetic switches, and linear induction voltage adders as are being developed in the Repetitive High Energy Pulsed Power (RHEPP) project⁽¹³⁾.

Example #1 - Large Area Surface Treatment with Ions or Electrons

Exploratory experiments have shown that electron and ion beams can be used to improve hardness, corrosion resistance, smoothness, and other material properties for use in hostile environments^(14,15). Energy is used efficiently, being deposited in a 1 to 20 μm thick layer, set by ion energy and type, over a large area, set by the beam diameter. Intense, pulsed, high energy ion beams can produce highly localized high surface temperatures, to melting or vaporization levels, followed by rapid thermal quenching to ambient temperatures. The rapid quenching can produce amorphous layers and other non-equilibrium microstructures. Results of surface treatment, in the Ion Beam Surface Treatment (IBEST) program using the RHEPP accelerator with a mixed carbon/proton beam driven by a 60 ns FWHM, 1 MeV, pulse, are discussed by Stinnett⁽¹⁶⁾. An example of surface hardening is shown in Figure 1, where tool steel surface hardness increased by a factor of 3 with ion beam surface treatment.

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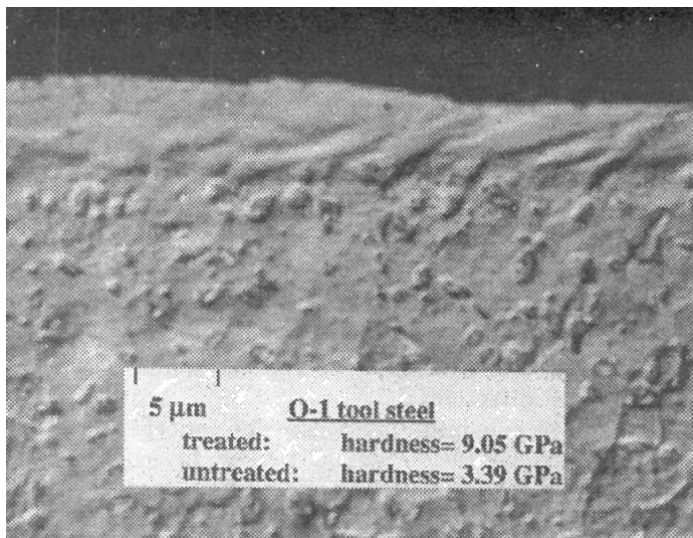


Figure 1 - Type O-1 tool steel treated with 60 ns pulse of mixed carbon/proton beam at 10 J/cm²

Figure 2 shows a titanium machined surface that has been smoothed from a roughness of about 10 μm to about 1 μm by four 300 keV pulses, at 2 to 4 J/cm², from a mixed proton/carbon beam. Smoothing and reduction in surface cracks by controlled surface melting and resolidification has also been demonstrated on polished alumina ceramic⁽¹⁶⁾. This technology has industrial applications such as extending bearing life and in bio-medical applications such as extending the life of devices like replacement hip ball and socket implants.

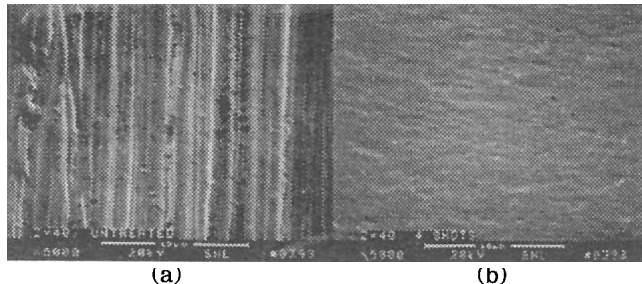


Figure 2 - Titanium machined surface before (a) and after (b) four pulses of 2-4 J/cm² mixed proton and carbon beam

Stinnett has also demonstrated surface smoothing of METGLAS®, an amorphous alloy used in high power magnetic switching systems. This has application in extending magnetic switch and blocking core life by reducing insulation wear. The pulsed ion beam method of melting and resolidification of the METGLAS® surface has the added advantage that the rapid quench rate, estimated at 10⁹ to 10¹⁰ °K/sec, may also preserve or enhance the low-loss magnetic properties of this material. Estimated surface treatment costs, using ion beams and the RHEPP high average power accelerator technology⁽¹³⁾, are \$0.30 per square meter.

Example #2 - High Temperature Ceramic Brazing

High energy electron beams can selectively deposit energy into a buried high-Z material interface as shown schematically in Figure 3a. The beam can heat the braze material above the surrounding material temperature as shown in Figure 3b. The beam energy can cause the

interface material to reach the melting temperature, allowing it to flow, wet the adjacent surfaces, and cause bonding of two ceramic surfaces or cause bonding of the ceramic material to an underlying metallic structure. Carbon-carbon composites may also be joined in this manner.

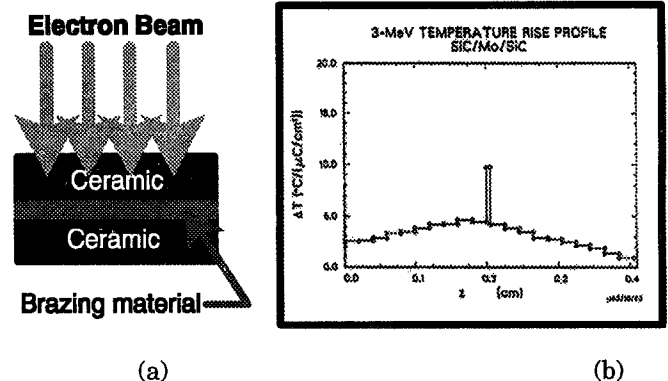


Figure 3 - E-beam brazing of ceramics geometry (a), and temperature rise profile for incident 3 MeV electron beam

Example #3 - Destruction of Organic Contaminants in Mixed Radioactive Wastes

The Hanford Nuclear Reservation, near Richland Washington, has 149 single-shell and 28 double-shell underground storage tanks that are used to store about 37 million gallons of a mixture of high level and low level radioactive wastes, and organic compounds. These materials are the result of processing and reprocessing activities, such as the PUREX (Plutonium Uranium Extraction) process, used to extract plutonium and uranium from irradiated reactor fuel. Twenty four tanks also contain ferrocyanide salts mixed in a sodium nitrate/sodium nitrite matrix. Conventional processes reduce the high level waste in volume and immobilized it for subsequent storage in a vitrification process that turns it into a glassy substance. The low level wastes are immobilized in a process which creates a cement grout. The separation of high and low level radioactive components and the subsequent immobilization processes can be hindered by the presence of organic materials that were used in the purification processes, such as EDTA. The organic compounds have undergone continual radiolysis, during the 30 to 40 years of storage, which makes identification of waste constituents difficult. The estimated accumulated total dose to the stored wastes amounts to between 30 and 100 Mrad. High average power electron beams from accelerators offer a potential solution to the Hanford organic waste problem.

Organics can be destroyed by the free radicals, e⁻_{aq}, H^{*}, and OH^{*}, generated by the passage of electron beams through aqueous solutions as described in previous work⁽¹⁷⁾. The reaction byproducts from this process are salts and CO₂. Electron beams may also be useful in destroying ferrocyanides⁽¹⁸⁾. Preliminary experiments, at Sandia⁽¹⁹⁾, have defined the total dose required to destroy organics in a simulant of the wastes stored in Hanford tank 101-SY. These experiments were conducted on two single pulse accelerators, KITE and a PI-112A machine, which furnished the same total dose, but at 2.6 x 10⁸ rads/sec and 2.7 x 10¹⁴ rads/sec respectively, to evaluate the effects of dose rate. The results are presented in Figure 4 below. This data shows that the 40 ns pulses are about three times

more effective than the 40 ms pulses in destroying the organics. Processing cost, including amortization, maintenance, and manpower, is estimated to be \$10.60 per gallon for a plant, based on RHEPP high average power accelerator technology⁽¹³⁾, sized to treat approximately 1200 gallons per hour or 860,000 gallons per month.

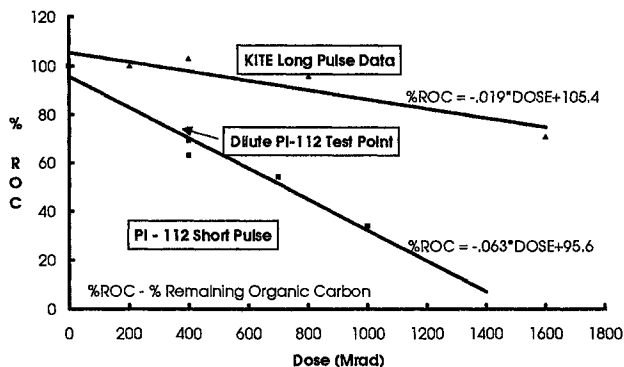


Figure 4 - Percent remaining organic content vs dose

Example #4 - Improving Asphalt Properties with High Energy Electron Beams

Asphalt is used on 93% of the roadways in the United States, and about \$10B is spent annually on highway maintenance and new construction. The typical asphalt pavement design lifetime is twenty years, but some inferior grade asphalts fail in significantly shorter times. Extended-life, high-performance asphalts could greatly reduce the annual maintenance costs. The chemical and engineering properties of asphalt are interrelated in a complicated manner since asphalt is composed of many complex hydrocarbon molecules. The average molecular weight of the composition has proven to be one good chemical indicator of mechanical properties, with higher average molecular weight correlated to stronger material properties. Reaction of asphalt with atmospheric oxygen is the major factor contributing to its hardening and embrittlement.

Electron beam processing is being studied as a possible method for pre-treating asphalt to improve its durability and strength. Electron beam irradiation has been shown to increase the average molecular weight of asphalt⁽²⁰⁾. Extended weatherability, reduced ball probe penetration under laboratory conditions, increased softening point temperature, enhanced bonding to the mineral aggregate, increased cross-linking and strengthening, and reduced viscosity-temperature susceptibility have been reported after electron and gamma-ray irradiation⁽²¹⁾. High average power beams, from RHEPP technology accelerators⁽¹³⁾, could process asphalt to a dose of 100 Mrad, at a rate of about one pound per second, for an estimated cost of a few cents per pound.

Example #5 - Atmospheric Electron Beam Welding (EBW)

Electron beams generated by existing EBW technology operate in the 50 to 300 keV regime. Beams with this energy typically deposit energy in ranges of 10 to 100 μ m for materials such as iron or titanium, which can cause heat-

ing, melting, and vaporization with sufficient average power input for welding. Because of the low beam energy, conventional electron beam welders operate in a vacuum environment, which limits the usefulness of the technology in some large industrial applications such as ship building. Non-vacuum, megavolt high energy electron beam (HEEB) welding may achieve workpiece standoff distances of as much as 10 cm without undue beam spot size growth from an initial diameter of 1 cm, due to Nordsieck beam expansion or nonlinear hose growth. Preliminary analysis using the IPROP code⁽²¹⁾, shows that beam expansion can be kept below a factor of 1.25 for 3 to 4 kA beams of 1 MeV electrons. Estimates of required beam power show that approximately 150 kW will be necessary for weld speeds of about 1 meter per minute. Pulsed electron beam accelerators, such as RHEPP devices, must be constrained to an upper limit of 1 to 2 kJ/gm of energy per pulse, set by material spallation effects. The repetition rate of these welding accelerators must be greater than 100 to 1000 Hz to prevent resolidification of the weld zone between pulses. Effects of the higher penetration depth of MeV beams on the heat affected zone (HAZ) and the weld quality is yet to be determined. Additional calculations for this application are underway and additional experiments using a number of different pulsed accelerators are planned.

Conclusion

The high peak power accelerator technology generated by defense needs over the past three decades is being adapted to a variety of industrial applications by the addition of heat management and reliability considerations. The characteristics of these high average power, short-pulse machines appear to offer new solutions to a number of manufacturing and environmental problems. We have identified a possible approach to matching the accelerator technology capabilities with a wide range of possible applications. High power beam application development is now in the phase where the availability of operational high average power, short-pulse accelerators makes feasibility demonstrations possible for a wide range of uses which appear to offer significant manufacturing and cost improvements.

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